ON SUBSTANTIAL SLOWING DOWN OF THE KINETICS OF FAST TRANSIENT PROCESSES IN FAST REACTOR

V.A. APSE
National Research Nuclear University MEPhI
Moscow, Russian Federation

E.G. KULIKOV
National Research Nuclear University MEPhI
Moscow, Russian Federation
Email: egkulikov@mephi.ru

G.G. KULIKOV
National Research Nuclear University MEPhI
Moscow, Russian Federation

A.N. SHMELEV
National Research Nuclear University MEPhI
Moscow, Russian Federation

Abstract

The neutron lifetime is an important parameter of the reactor kinetics. When the inserted reactivity is more than the effective fraction of delayed neutrons, the reactor kinetics becomes very rapid. The fast reactor kinetics can be slowed down by increasing the neutron lifetime. The possibility of using lead isotope ^{208}Pb as a neutron reflector with specific properties in the lead-cooled fast reactor is considered. A point kinetics model has been chosen to assess the emerging effects. The model takes into account the effects produced by neutrons returning from ^{208}Pb-reflector to the reactor core. Such specific properties of ^{208}Pb as large atomic weight, weak neutron absorption allow neutrons from the reactor core to penetrate deeply into ^{208}Pb-reflector, slow down there and have a noticeable probability to return to the reactor core and affect the chain fission reaction. The neutrons coming back from ^{208}Pb-reflector have a long "dead-time" which represents the sum of times when neutrons leave the reactor core entering ^{208}Pb-reflector and then diffuse back into the reactor core. During the "dead-time" these neutrons can't affect the chain fission reaction. The neutrons returning from deep layers of ^{208}Pb-reflector are close to the delayed neutrons in the terms of time delay. Moreover, the number of the neutrons coming back from ^{208}Pb-reflector considerably exceeds the number of the delayed neutrons. As a result, the neutron lifetime formed by the prompt neutron lifetime and the "dead-time" of the neutrons from ^{208}Pb-reflector can be substantially increased. This can lead to the longer reactor period, which mitigates the effects of prompt super-criticality. To conclude, the use of lead isotope ^{208}Pb as a neutron reflector can improve significantly safety of the fast reactor operation.

1. INTRODUCTION

As it was demonstrated in a series of scientific publications [1–4], application of radiogenic lead with dominant content of lead isotope ^{208}Pb as a coolant and as a neutron reflector around the lead-cooled fast reactor core provides some important advantages. One of the most significant benefits from these applications of radiogenic lead instead of natural lead consists in a possibility for substantial (by several orders of magnitude) elongation of mean prompt neutron lifetime l_{prt}, from the level of decimal fractions of microsecond up to the level of decimal fractions of millisecond, i.e. up to the typical values of thermal light-water reactors.

So radical elongation of mean prompt neutron lifetime is caused by unique properties of lead isotope ^{208}Pb, double-magic nuclide with completely closed proton and neutron shells. That is why micro cross-sections of radiative neutron capture by ^{208}Pb (~0.23 mb for thermal neutrons) are significantly smaller (by about two orders of magnitude [5]) than those of natural lead and graphite (~174 mb and ~3.9 mb, respectively, in thermal energy point). This advantage of ^{208}Pb takes place within sufficiently wide energy range of the reactor neutrons, from thermal energy point up to several tens of kilo electron-volts.

In addition, the excitation levels of ^{208}Pb nucleus are placed at the higher energies (the first excitation level is 2.61 MeV) in comparison with the excitation levels of other lead isotopes (0.57–0.90 MeV) [5]. That is why the energy threshold of inelastic neutron scattering by ^{208}Pb is higher than that of other lead isotopes. On the other side, isotope ^{208}Pb is a weak neutron moderator through the channel of elastic neutron scattering because of its large atomic weight.

As a result of weak neutron absorption and weak neutron slowing down by isotope ^{208}Pb, those neutrons which were generated in the reactor core and which came from the reactor core to the physically thick ^{208}Pb-reflector can stay there for a sufficiently long time period. Afterwards, these neutrons can come back to the reactor core and participate in the chain fission reaction (CFR) but with a certain time delay. Such a time delay of neutron staying in a weak neutron absorber can elongate substantially mean prompt neutron lifetime and, as a consequence, provide some slowing down of the CFR propagation at reactivity-induced accidents.

Besides, insertion of the inner ^{208}Pb-cavity into central region of the reactor core opens a supplementary opportunity to create a zone where resonance, epithermal and thermal neutrons could be accumulated. These relatively slow neutrons are able to reduce rate of the CFR propagation quite similarly to the neutrons coming from the reactor core to the outer ^{208}Pb-reflector and coming back to the reactor core after a certain time delay. Accumulation of resonance neutrons in the inner ^{208}Pb-cavity can influence favorably on the stabilizing action of Doppler-effect under accidental elevation of fuel temperature.

2. GEOMETRICAL MODEL OF LEAD-COOLED FAST REACTOR

The current projects of lead-cooled fast reactors consider very flattened core with high degree of flatness [6–8]. So, it seems acceptable to use one-dimensional plane (axial) model of the lead-cooled fast reactor in numerical studies of key reactor parameters.

A series of numerical studies was carried out to clarify reasonability of the prerequisites mentioned above on potential benefits from applications of lead isotope ^{208}Pb as a material of the inner cavity, as a coolant and as a neutron reflector in the fast reactor design. The computer code TIME26 [9] was used in these numerical studies. This computer code is based on the use of diffusion 26-group approximation in order to determine main neutron-physical parameters of one-dimensional models of fast reactors and accelerator-driven facilities. The computer code TIME26 applies auxiliary code ARAMACO-S1 [10] for processing of evaluated nuclear data library ABBN-78 with generation of zone-dependent sets of 26-group micro cross-sections.

Numerical studies were carried out for one-dimensional axial model of the lead-cooled fast reactor loaded with mixed uranium-plutonium nitride fuel. Geometrical parameters of the reactor fuel rods were taken from the paper [8]: diameter of fuel pellet – 7.7 mm, thickness of fuel-cladding gap – 0.2 mm, thickness of steel cladding – 0.5 mm, pitch of triangular fuel lattice – 13.6 mm, height of fuel column – 110 cm.

Axial model of the reactor represents the following sequence of spatial zones. The first zone, namely the inner lead cavity with variable thickness, is placed in center of the reactor core, adjacently to the axis of symmetry. Top half of the reactor core (with fixed thickness – 55 cm because of axial symmetry) is placed over the inner lead cavity. The outer lead reflector (250 cm in thickness) is placed over the reactor core. Natural lead and lead isotope ^{208}Pb were considered as materials of the inner cavity, coolant and neutron reflector (Fig. 1).

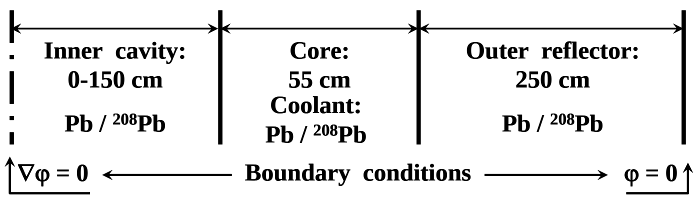

FIG. 1. Geometrical layout of the fast reactor with the inner cavity and the outer reflector.

Critical content of plutonium fraction in the mixed uranium-plutonium nitride fuel was determined at zero thickness of the inner cavity. Then, the following neutron-physical parameters were calculated for various thickness of the inner cavity: effective neutron multiplication factor K_{eff}, neutron energy spectrum in the inner cavity, mean prompt neutron lifetime l_{prt} and the Doppler constant $K_D=T\cdot(dK_{eff}/dT)$, where T is the fuel temperature.

For more vivid presentation of neutron spectra multi-group neutron fluxes were summarized into the following three wider groups: fast high-energy neutrons ($E_n > 21.5$ keV), resonance neutrons whose energies E_n correspond to the resonance range of ^{238}U (from 4.65 eV to 21.5 keV), epithermal and thermal neutrons ($E_n <$ 4.65 eV).

3. RESULTS OF NEUTRON-PHYSICAL COMPUTATIONS FOR AXIAL MODEL OF THE FAST REACTOR

Axial distributions of neutron spectra and neutron fluxes are presented in Fig. 2 and 3 for the following two cases: natural lead is used in the inner cavity, the reactor core and the outer reflector; lead isotope ^{208}Pb is used in the inner cavity, the reactor core and the outer reflector. Thickness of the inner cavity (200 cm) was fixed in these considerations.

Spatial distributions of neutron spectra are very close each other in both cases. This is seen especially clearly for fraction of fast neutrons with maximal value in the reactor core and recession in the inner cavity and in the outer reflector. On the contrary, fractions of resonance, epithermal and thermal neutrons are characterized by minimal values in the reactor core with the raise in the inner cavity and in the outer reflector. The raise of resonance neutron fraction is larger in the case of natural lead while the raise of epithermal and thermal neutron fractions is larger in the case of ^{208}Pb. These different raises can be explained by the fact that fast neutrons play here a role of neutron source for other energy groups and the smaller neutron absorption by ^{208}Pb in comparison with natural lead.

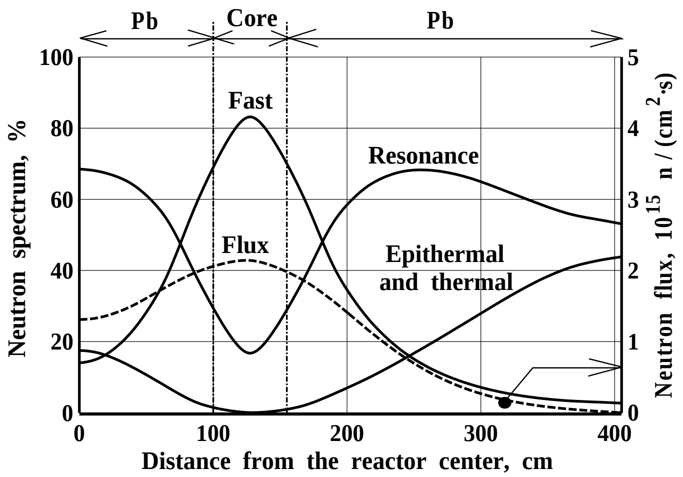

FIG. 2. The case of natural lead. Spatial distributions of neutron spectrum and neutron flux

The weaker neutron absorption by ^{208}Pb results in the following effects. Neutron flux in the inner Pb-cavity is substantially smaller than that in the reactor core while neutron flux in the inner ^{208}Pb-cavity is remarkably larger than that in the reactor core (Fig. 3). Neutron flux in the center of the inner ^{208}Pb-cavity is higher by a factor of 2.5 than neutron flux in the center of the inner Pb-cavity. The larger neutron flux and the larger fraction of slow neutrons are able to form favorable conditions for more effective transmutation of long-lived fission products in the inner ^{208}Pb-cavity.

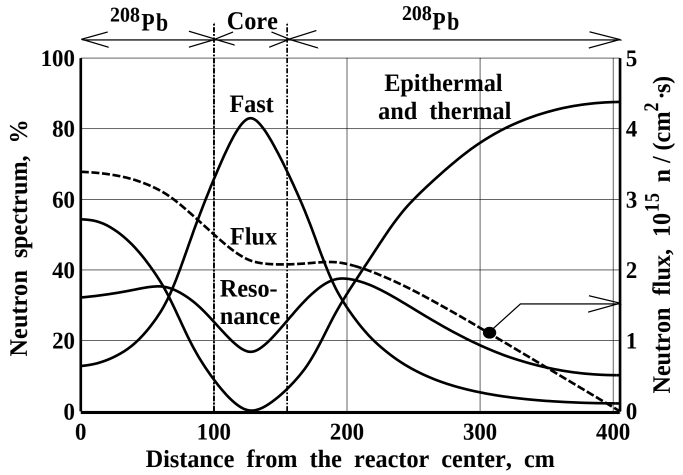

FIG. 3. The case of ^{208}Pb. Spatial distributions of neutron spectrum and neutron flux

As is seen from Fig. 2 and 3, substitution of ^{208}Pb for natural lead in the reactor core produced no any remarkable change in neutron spectrum. This means that main neutronic parameters of the reactor core (including so important factor as the fuel breeding ratio) will remain unchanged also. In addition, neutron spectra in fast reactors are substantially defined by the slowing-down step. The neutron slowing-down step of lead is lower by a factor of 9 than that of sodium, the mostly used coolant of fast reactors.

Space-averaged neutron spectrum in the inner cavity is presented in Fig. 4 as a function of the cavity thickness (from 50 cm up to 300 cm) for the following two cases: natural lead or ^{208}Pb is used as a material of the inner cavity.

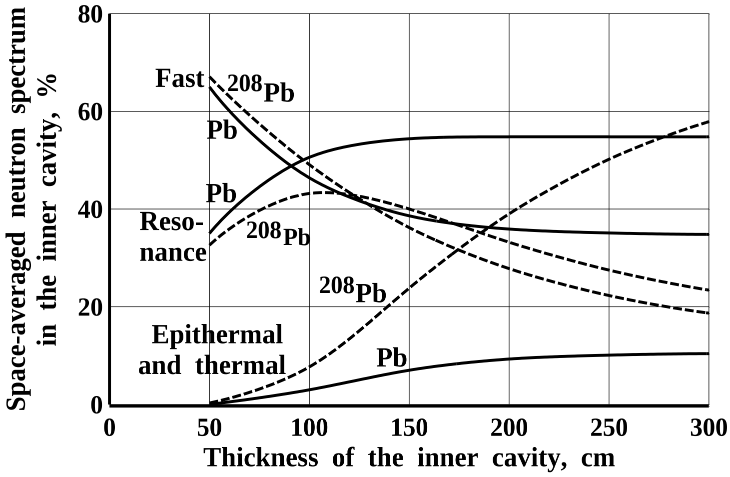

FIG. 4. Space-averaged neutron spectrum in the inner cavity as a function of its thickness

As is seen, lead isotope ^{208}Pb is the more effective (in comparison with natural lead) converter of fast neutrons, which come from the reactor core into the inner cavity, to epithermal and thermal neutrons. Indeed, if thickness of the inner cavity is 200 cm, then fraction of epithermal and thermal neutrons in neutron spectrum of the inner ^{208}Pb-cavity is equal to 39% while the same fraction in the inner Pb-cavity is equal to 9% only, i.e. four times lower. If the inner cavity was thickened up to 300 cm, then these fractions became equal to 58% in ^{208}Pb-cavity and 10% in Pb-cavity, i.e. about six times lower.

So large fractions of epithermal and thermal neutrons in the inner ^{208}Pb-cavity create some prerequisites for elongation of mean prompt neutron lifetime, and for strengthening of the stabilizing Doppler-effect at accidental temperature elevation. The results obtained in appropriate computations are presented in Fig. 5 and 6.

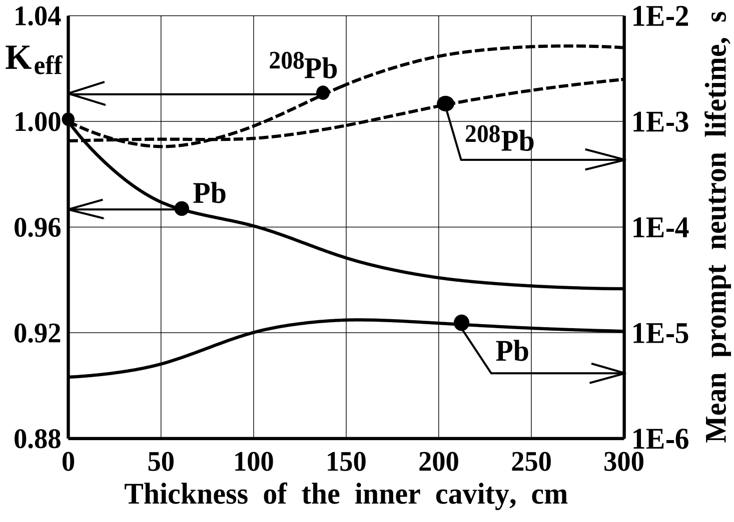

FIG. 5. Criticality and mean prompt neutron lifetime as functions of the inner cavity thickness

The following conclusions can be derived from these dependencies. If the inner Pb-cavity becomes thicker, then effective neutron multiplication factor K_{eff} decreases in a monotonous manner, mean prompt neutron lifetime remains at the level of ~10 microseconds, the Doppler constant is negative and equal to about - 0.010.

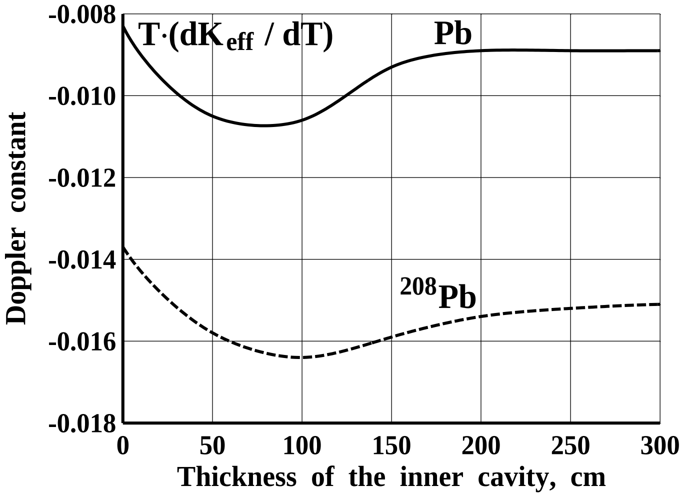

FIG. 6. Dependence of the Doppler constant on thickness of the inner cavity

If the inner ^{208}Pb-cavity becomes thicker, then effective neutron multiplication factor K_{eff} decreases at first, then goes through a minimal value and increases above criticality. Mean prompt neutron lifetime l_{prt} elongates in a monotonous manner. At thickness of 300 cm l_{prt} reaches ~2.5 milliseconds, and this value is not a limit. The Doppler constant is negative and equal to about - 0.016, i.e. by 1.5 times larger (in absolute value) than that in the case of natural lead.

All these distinctions are caused by the facts that lead isotope ^{208}Pb is the weaker neutron absorber and more effective of fast fission neutrons into resonance, epithermal and thermal neutrons in comparison with natural lead. These low-energy neutrons are characterized by the longer lifetimes. In addition, if these slow neutrons come back to the reactor core, then they are able to intensify the CFR and, thus, upgrade the reactor criticality. Under an accidental fuel warming-up, absorption of resonance neutrons is intensified, and, as a consequence, the stabilizing Doppler-effect can be strengthened. The favorable effect of using ^{208}Pb was demonstrated by the point kinetics analysis of a simple reactivity-induced accident and published in Ref. 3.

4. CONCLUSIONS

The results presented in the paper allowed us to make the following conclusions.

1. Insertion of the inner lead cavity into central region of the reactor core opens a possibility to create a zone containing mainly resonance, epithermal and thermal neutrons. Lead isotope ^{208}Pb is the more suitable material for creation of such neutron spectrum in the inner cavity as compared with natural lead.

2. These resonance, epithermal and thermal neutrons in the inner ^{208}Pb-cavity are able to contribute significantly to the elongation of mean prompt neutron lifetime l_{prt} thus supplementing the same effect produced by the outer ^{208}Pb-reflector. Substitution of ^{208}Pb for natural lead in the outer reflector transfers l_{prt} from the microsecond range to the millisecond range (from 3.8 μs up to 0.65 ms). Additional insertion of the inner ^{208}Pb-cavity elongates l_{prt} by a factor of four (up to 2.5 ms). The elongation of mean prompt neutron lifetime creates favorable conditions for mitigation of accidental power excursions.

3. Those resonance, epithermal and thermal neutrons which are accumulated in the inner ^{208}Pb-cavity with the further return to the reactor core are able to intensify the CFR and upgrade the reactivity margin.

4. Under accidental elevation of the reactor temperature those resonance, epithermal and thermal neutrons, which come back to the reactor core from the inner ^{208}Pb-cavity, are able to strengthen the stabilizing Doppler-effect. The Doppler constant in the case of inner ^{208}Pb is negative and larger (in absolute value) by a factor of 1.5 than that in the case of natural lead.

5. High flux of low-energy neutrons in large volume of the inner ^{208}Pb-cavity opens a possibility for effective transmutation of long-lived fission products with sufficient place for their disposition.

6. The paper analyzes some potential advantages from using ^{208}Pb in fast reactors as a coolant and neutron reflector. Main difficulty consists in the necessity to produce large amount of lead with dominant content of ^{208}Pb. One way is to enrich natural lead (52.4% ^{208}Pb) by means of well-known isotope separation technologies. Another way is to extract radiogenic lead with high (about 93%) content of ^{208}Pb from natural thorium-bearing ores. Probably, mining, recovery and additional enrichment of radiogenic lead up to a necessary level could solve the problem.

REFERENCES

[1] APSE, V.A., SHMELEV, A.N., SIROTKIN A.M., On a possibility to improve some neutron-physical, thermal and hydraulic parameters of power fast reactors at application of radiogenic lead as a coolant, Nuclear Physics and Engineering 2 (2010) 184–195.

[2] KULIKOV, G.G., SHMELEV, A.N., APSE, V.A. et al., On a possibility to apply radiogenic lead in nuclear power industry, Communications of Higher Schools. Nuclear Power 3 (2010) 39–47.

[3] SHMELEV, A.N., KULIKOV, G.G., KRYUCHKOV, E.F., APSE, V.A., KULIKOV, E.G., Application of Radiogenic Lead with Dominant Content of ^{208}Pb for Long Prompt Neutron Lifetime in Fast Reactor, Nuclear Technology **183** 3 (2013) 409–426.

[4] KULIKOV, G.G., SHMELEV, A.N., KULIKOV, E.G. et al., Capability of the reflector neutrons to strengthen resistance of chain fission reaction to rapid power excursions, Atomic Energy **123** 6 (2017) 351–352.

[5] SHIBATA, K. et al., JENDL-4.0: a new library for nuclear science and engineering, Nuclear Science and Technology **48** 1 (2011).

[6] ORLOV, V.V., “Conceptual evolution of fast reactors. Concept of the lead-cooled fast reactor BREST”, The International Seminar “Fast Reactor and Nuclear Fuel Cycle with Inherent Safety for Large-Scale Nuclear Power. Fuel Balance, Economics, Safety, Wastes, Nonproliferation”, Moscow (2000).

[7] ORLOV, V.V., LEONOV, V.N., SILA-NOVITSKY et al., “Design of the reactor BREST. Experimental studies for justification of conceptual BREST reactor design”, The International Seminar “Fast Reactor and Nuclear Fuel Cycle with Inherent Safety for Large-Scale Nuclear Power. Fuel Balance, Economics, Safety, Wastes, Nonproliferation”, Moscow (2000).

[8] BORISOV, O.M., ORLOV, V.V., NAUMOV, V.V. et al., “Requirements to the reactor BREST core design”, The International Seminar “Fast Reactor and Nuclear Fuel Cycle with Inherent Safety for Large-Scale Nuclear Power. Fuel Balance, Economics, Safety, Wastes, Nonproliferation”, Moscow (2000).

[9] APSE, V.A., SHMELEV, A.N. Applications of the computer code TIME26 in the course designing of fast reactors and accelerator-driven facilities. Training manual, MEPhI, Moscow (2008).

[10] NIKOLAEV, M.N., ABAGYAN, L.P., TIBULYA, A.M., et al. Package of the computer codes ARAMACO for automatic generation of macroscopic constants, Institute on Physics and Power Engineering, Obninsk (1972).